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J.A. Tanis, S.M. Shafroth, J.E. Willis, M. Clark
J. Swenson, E.N. Strait, J.R. Mowat

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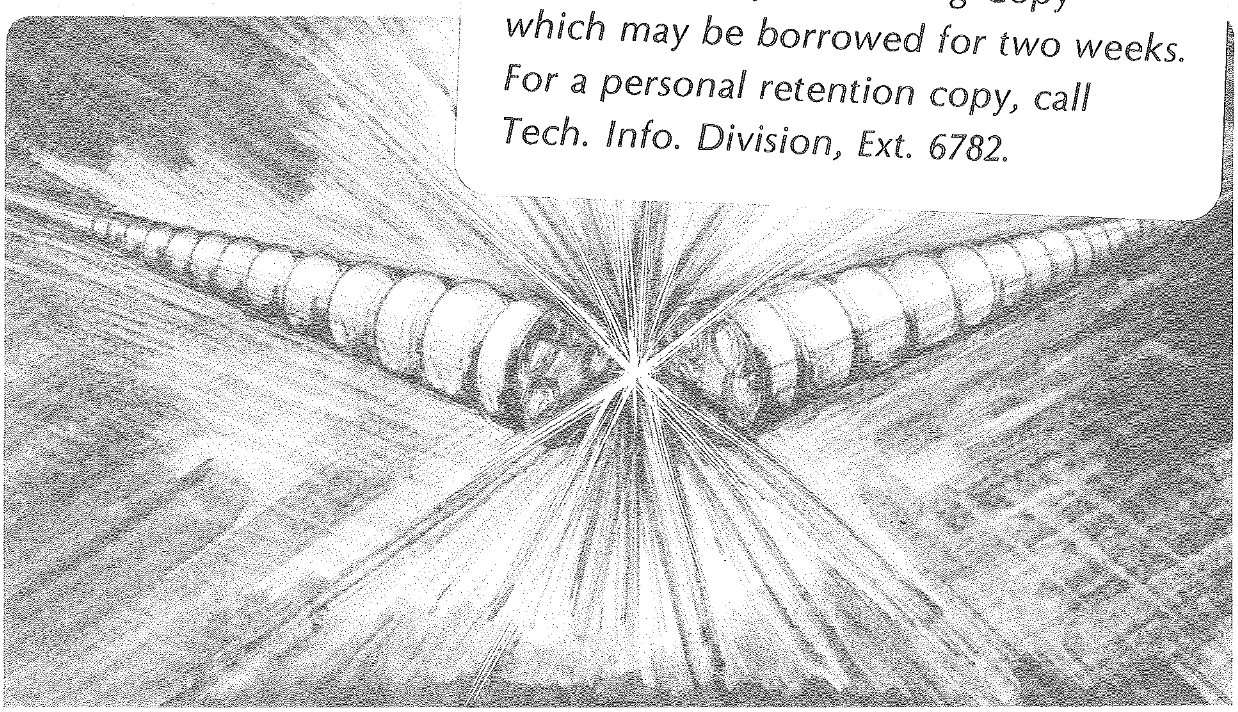

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Dielectronic Recombination in S+Ar Collisions*

J. A. Tanis

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

S. M. Shafroth, J. E. Willis , M. Clark, and J. Swenson

Department of Physics and Astronomy
University of North Carolina
Chapel Hill, N.C. 27514

E. N. Strait

Physics Department
Macalester College
St. Paul, MN 55105

and

J. R. Mowat

Department of Physics
North Carolina State University
Raleigh, NC 27607

ABSTRACT

Dielectronic recombination is observed for 70 MeV S^{13+} + Ar collisions. In addition, radiation following capture into high n states without accompanying excitation is measured for charge states q = 14+ to 16+. The results are used to determine the fraction of capture events which result in K-shell radiation. Possible applications to radiative loss processes in fusion plasmas and stellar atmospheres are discussed.

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Dielectronic recombination occurs when an ion in charge state q captures a continuum electron and simultaneously excites an electron from the ground state configuration, resulting in a doubly excited state. This process is just the inverse of the Auger effect. Dielectronic recombination is a process not only of fundamental interest but also is thought to be an important energy loss mechanism in thin high temperature plasmas.[1-3] Measurement of dielectronic recombination (DIREC) cross sections over a wide range of energies (temperatures) and ion masses may have important applications in the development of laboratory plasmas and in the understanding of astrophysical plasmas. Measurement of the DIREC cross section is difficult, due in part to similar processes taking place at the same time such as collisional excitation and ionization.

In this Letter we report the first identification of DIREC in heavy ion-atom collisions. Sulfur K x-ray emission following electron capture has been measured for 70 MeV S^{q+} (q = 13-16) ions incident on argon. K radiation resulting from capture was isolated by detecting coincidences between S K x rays and electron capture events. In addition to dielectronic recombination, cross sections for K radiation following capture into a high n state ($n \geq 2$) without accompanying K-shell excitation have also been determined. Total cross sections for K radiation following single capture increase from $3.7 \times 10^{-21} cm^2$ to $4.5 \times 10^{-18} cm^2$ for S charge states 13+ to 16+.

This work was performed at the Triangle Universities Nuclear Laboratory using the FN Tandem Van de Graaff. Sulfur ions from the TUNL sputter ion source were accelerated to 70 MeV and poststripped to achieve high charge states. Following magnetic analysis, the selected charge state beam was passed through a differentially pumped gas cell containing typically 100-200 μ of Ar as measured with a capacitance manometer. Target gas pressures were such that $\lesssim$ 15% of the incident beam changed charge state in passage through the target and for S^{13+} this fraction was $\lesssim$ 7%. Furthermore, it is estimated that < 2% of the beam changed charge prior to entering the target cell. After emerging from the gas cell, the beam was electrostatically analyzed into its charge state components. Ions which underwent single (or double) capture were detected in a silicon surface barrier detector. X rays emitted from the target were detected with a Si(Li) detector mounted at 90° to the beam. X rays were viewed through a 6.4 μm Mylar window which sealed the gas cell.

Coincidences between single (or double) capture events and S K x rays were detected with a time-to-amplitude converter (TAC). A window was set on the S K x rays using a single-channel-analyzer (SCA) so that only <u>projectile</u> x rays in coincidence with capture events would be recorded. For incident S^{16+}, radiative decays occur in the presence of two K vacancies, i.e., hypersatellite transitions, and are shifted by ∿ 140 eV to higher energy. Hence the window on the SCA had to be reset to account for this shift. This shift is somewhat lower than that expected ($\Delta E \sim$ 160 eV) for a hypersatellite transition.[4] This lower shift can be understood from the fact that a significant fraction of the S^{16+} capture events result in capture of two electrons (see Table 1). If one of the electrons in a double capture event is captured directly into the K shell, then there would be no hypersatellite shift for such an ion, thereby accounting for a lower than expected x-ray energy shift for incident S^{16+}. It is well known that K-to-K electron transfer is highly probable in such collisions.[5]

A measure of the integrity of the coincidence detection system was obtained for incident S^{16+} ions, by looking for projectile K x rays in coincidence with emerging S^{16+} ions for which there should be no real coincidences. We did, in fact, observe only random coincidences as expected. This result also indicates that charge stripping after emerging from the target and prior to charge state analysis is minimal. If this were a significant charge changing process, then an incident S^{16+} ion which captures an electron in the target and emits a K x ray could be re-stripped to S^{16+} prior to charge selection and be recorded as a "real" coincidence.

Singles spectra for both particles and x rays as well as the coincidence spectrum were recorded. Measured x-ray yields were corrected for detection efficiency and subtended solid angle. Normalization of the incident beam intensity was accomplished in two ways: (1) measurement of the analyzed ion intensity in each of the charge states and (2) from the measured S and Ar total K x-ray production cross sections in a separate experiment. The total absolute error in the coincidence K x-ray cross sections obtained is estimated to be $\pm 30\%$. Sufficient counts were obtained in the TAC spectrum so that statistical errors were less than 3% for q = 14+ to 16+ and less than 10% for q = 13+. The counting time to obtain sufficient statistics for q = 13+ was about four to five hours.

Cross sections for K x-ray emission following capture as well as total cross sections for single and double capture were obtained for incident sulfur charge states q = 13+ to 16+. The results are shown in Table I and Figs. 1-3.

In Figure 1 we show the total cross section for K-shell radiation following capture, which denote by σ_{CAPRAD}. This is just the sum of the dielectronic recombination cross section σ_{DIREC} and the cross section for K radiation following capture into a high n state, σ_{NREC}, i.e.,

$$\sigma_{CAPRAD} = \sigma_{DIREC} + \sigma_{NREC} .$$

Only for S^{13+} (Li-like sulfur) can the cross section be attributed totally to DIREC since the initial three-electron state of the beam is $1s^2 2s$. For He-like S (q=14+), there is a significant metastable fraction 1s2s ($^3S_1$) in the beam for which K radiation following high n-state capture becomes possible. Unfortunately, the metastable fraction of the beam is unknown. For ground state S^{14+}, only the DIREC process is possible. For S^{15+} nearly all of the K radiation is believed to result from high n-state capture, while for S^{16+}, this is the <u>only</u> possible K-radiative decay mode. It is seen that σ_{CAPRAD} increases by more than three orders of magnitude in going from q = 13+ to 16+.

Also shown in Fig.1 is the cross section for K radiation following double capture by S^{15+} ions. This cross section is seen to be about an order of magnitude lower than that following single capture. This double capture radiative recombination mechanism was measured only for incident S^{15+} ions.

We know of no theoretical calculations with which to directly compare our measured DIREC cross section for 70 MeV S^{13+} ions. In the first place, we know of no calculations for the dielectronic recombination of Li-like sulfur ions at this energy and, secondly, calculations do not exist for DIREC in ion-atom collisions.

We can, however, get an order of magnitude comparison by using the theoretical results of Jacobs[6] <u>et al</u>. for highly stripped Fe ions. A 70 MeV sulfur ion has a velocity of 2.06×10^9 cm/sec which corresponds to an electron energy of 1.2 keV. This is equivalent to a temperature of $\log_{10} T_e(K)=7.1$. From Jacobs <u>et al</u>. the dielectronic recombination rate for Li-like Fe is $\alpha_{DIREC} = 1.23 \times 10^{-11}$ cm^3/s. Since $\alpha = \langle\sigma v\rangle$ where v = the electron velocity, this gives $\sigma_{DIREC} = 6.0 \times 10^{-21}$ cm^2 which is to be compared with our experimental value of 3.7×10^{-21} cm^2 for Li-like sulfur. It is emphasized that this comparison is only qualitative since the quantity $<\sigma v>$ is calculated for ions and electrons with a distribution of relative velocities, whereas in the present experiment the ions and electrons have a (nearly) definite relative velocity. Furthermore, the comparison between theory and experiment was made for ions of different atomic number due to the lack of available calculations for sulfur ions.

The single and double capture cross sections for 70 MeV S^{q+} ions in Ar gas were determined from the charge changed fractions and are listed in Table I. From these capture cross sections and the data of Fig. 1 we obtain the ratio $\sigma_{CAPRAD} / \sigma_{q,q-n}$ which is the fraction of single or double capture events which result in K radiation, shown in Fig. 2. This fraction is seen to increase rapidly from 0.0004 to 0.3 for charge states q = 13+ to 16+. Hence, we conclude that radiative recombination becomes a significant recombination mechanism for highly stripped ions. For S^{15+} we see that 13% of the single capture events result in K radiation, while 9% of the double capture events result in K radiation.

Finally, in Fig. 3 we show the fraction of S projectile K x rays which result from <u>capture</u> events as opposed to <u>excitation</u> or <u>ionization</u> events. This is just the ratio of coincidence K x rays to singles K x rays. For single capture, this ratio varies from 0.17 to 0.67 for q = 13+ to 16+. For S^{16+}, all of the x rays must result from electron capture and hence the ratio Y_{COINC} / Y_{SINGLE} should equal unity. The result plotted for S^{16+} is for single capture only, and hence, K x rays following double capture are not included. The double capture fraction was measured to be about half that found for single capture and so, we conclude that the x rays following electron capture would be accounted for. This also indicates that the coincidence detection efficiency is nearly 100%.

As mentioned previously, dielectronic recombination, observed in the present work for a highly stripped ion incident on a multielectron target atom, is expected to be an important recombination mechanism for highly stripped impurity ions in a plasma. If the interaction is with the loosely bound electrons in the target, then it may be possible to simulate the recombination of the electrons in a fusion or astrophysical plasma with the same process in an ion-atom collision. Evidence for the fact that radiative capture of loosely bound target electrons is approximately equivalent to capture of a free electron has already been obtained[7-9].

Furthermore, if the coincidence K x rays do indeed result from interactions with the loosely bound target electrons, then the remaining K x rays can be attributed to interactions with the target nucleus (see Fig. 3). This suggests the possibility that K-radiative events due to target ions and electrons may be separately determined. If a target such as H or He were used in which all of the target electrons may be considered "free" with respect to the fast projectile, then coincidence x rays would represent radiative transitions due to electron capture, while the remaining x rays would represent radiative transitions resulting from excitation or ionization by the positive nucleus. In total then, such a collision system might simulate radiative losses due to collisions of both electrons and ions with highly stripped ions in a plasma.

In summary, we have reported the first observation of dielectronic recombination in ion-atom collisions. In addition, we have determined K-radiative cross sections following high n-state capture for charge states for which this mechanism dominates over dielectronic recombination. These results were used to determine the fraction of capture events which results in K-shell radiation. Possible applications to radiative loss processes in a plasma were considered. To the extent that the recombination processes studied here in ion-atom collisions simulate the same processes for free electrons in a plasma, it may be possible to use such measurements to test theoretical calculations of radiative loss rates in plasmas and also to provide experimental estimates of these radiative losses.

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† Present address: Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008.

†† Present address: Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

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TABLE I. Cross sections for K x-ray emission following electron capture and total cross sections for single and double capture by 70 MeV S^{q+} ions incident on Ar.

Incident	σ_{CAPRAD} (kb)		$\sigma_{q,\,q-n}$ (10^{-18} cm^2)		Y_{COINC}/Y_{SINGLE}	
q	q-1	q-2	q-1	q-2	q-1	q-2
13	3.7 ± 1.1	---	9.55 ± 0.96	1.67 ± 0.17	0.17 ± 0.02	---
14	150 ± 45	---	18.2 ± 1.8	3.64 ± 0.36	0.43 ± 0.03	---
15	2200 ± 660	300 ± 90	16.7 ± 1.7	3.33 ± 0.33	0.52 ± 0.02	0.24 ± 0.01
16	4500 ± 1350	---	15.2 ± 1.5	7.27 ± 0.73	0.67 ± 0.05	---

FIGURE CAPTIONS

FIG. 1. Total cross section for projectile K-shell radiation following single (q-1) or double (q-2) capture for 70 MeV S^{q+} ions (q=13-16) incident on Ar. This cross section is the sum of the K radiative cross sections resulting from dielectronic recombination and capture into high n states. The line is drawn to guide the eye.

FIG. 2. Fraction of single (q-1) or double (q-2) capture events which results in projectile K radiation. $\sigma_{q,q-n}$ represents the single (n=1) or double (n=2) capture cross section.

FIG. 3. Yield of S projectile K x rays which results from capture events (Y_{COINC}) compared to total S K x-ray emission (Y_{SINGLE}) which includes x rays from excitation and ionization events.

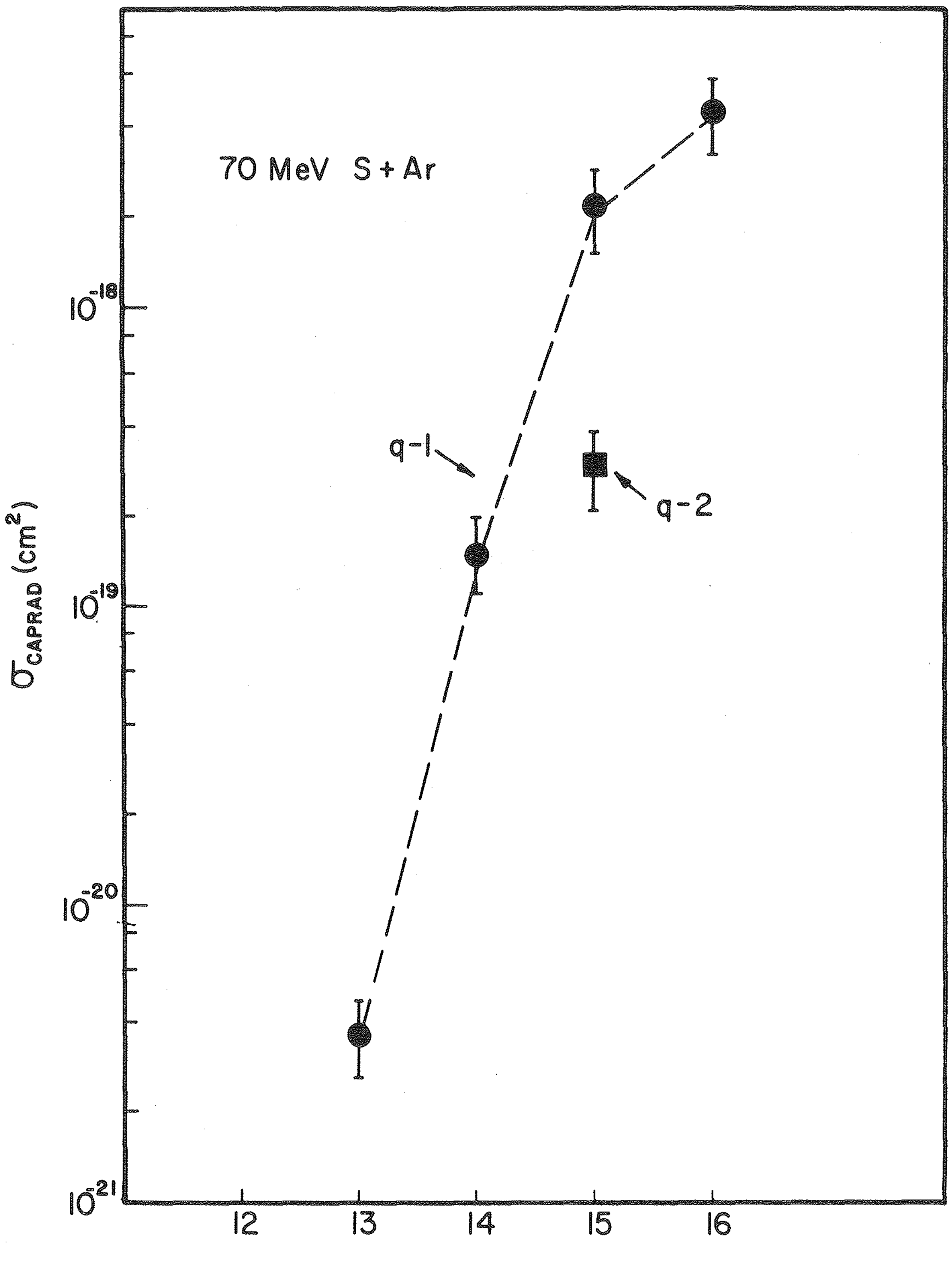

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Fig. 1

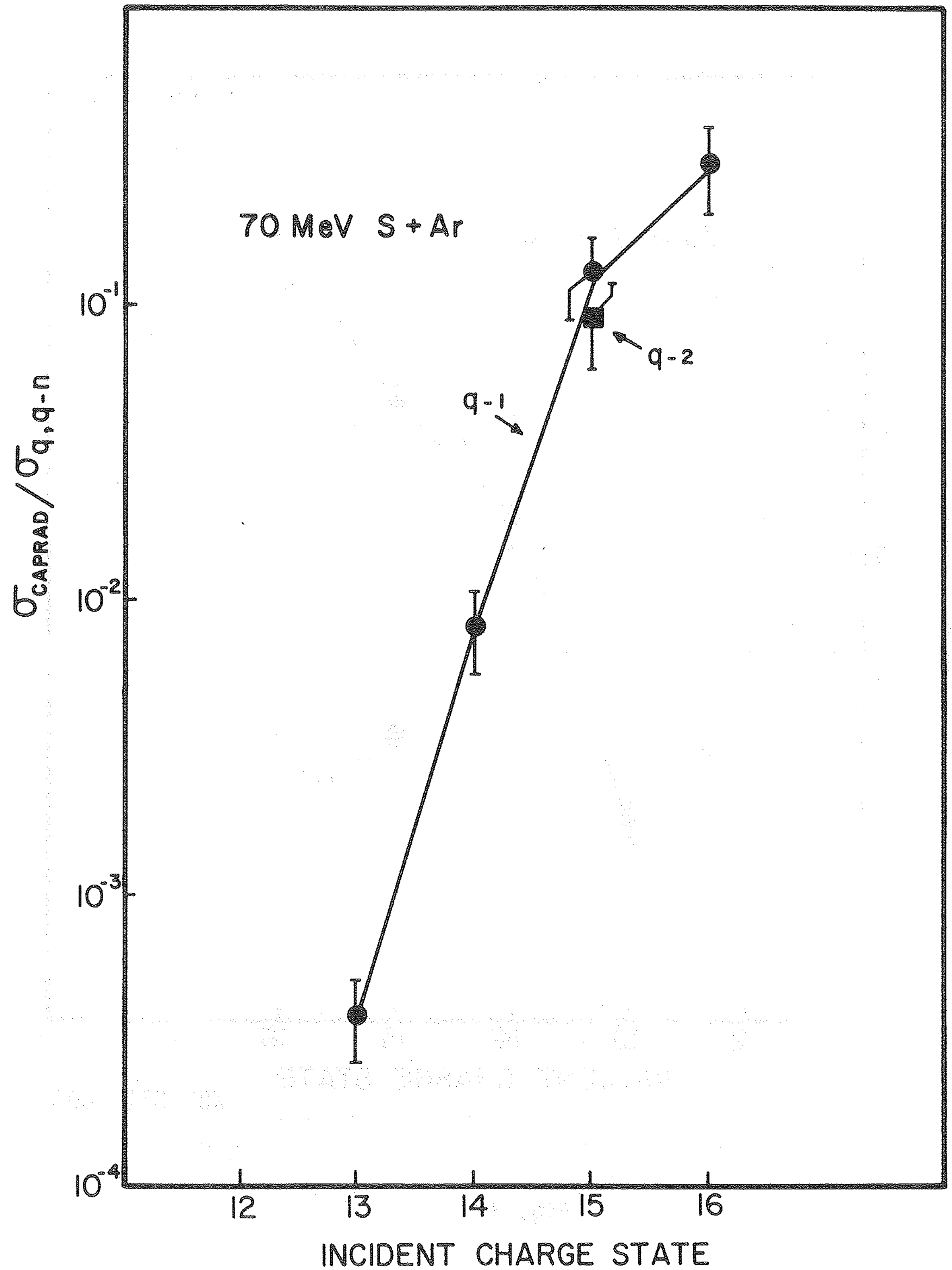

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Fig. 2

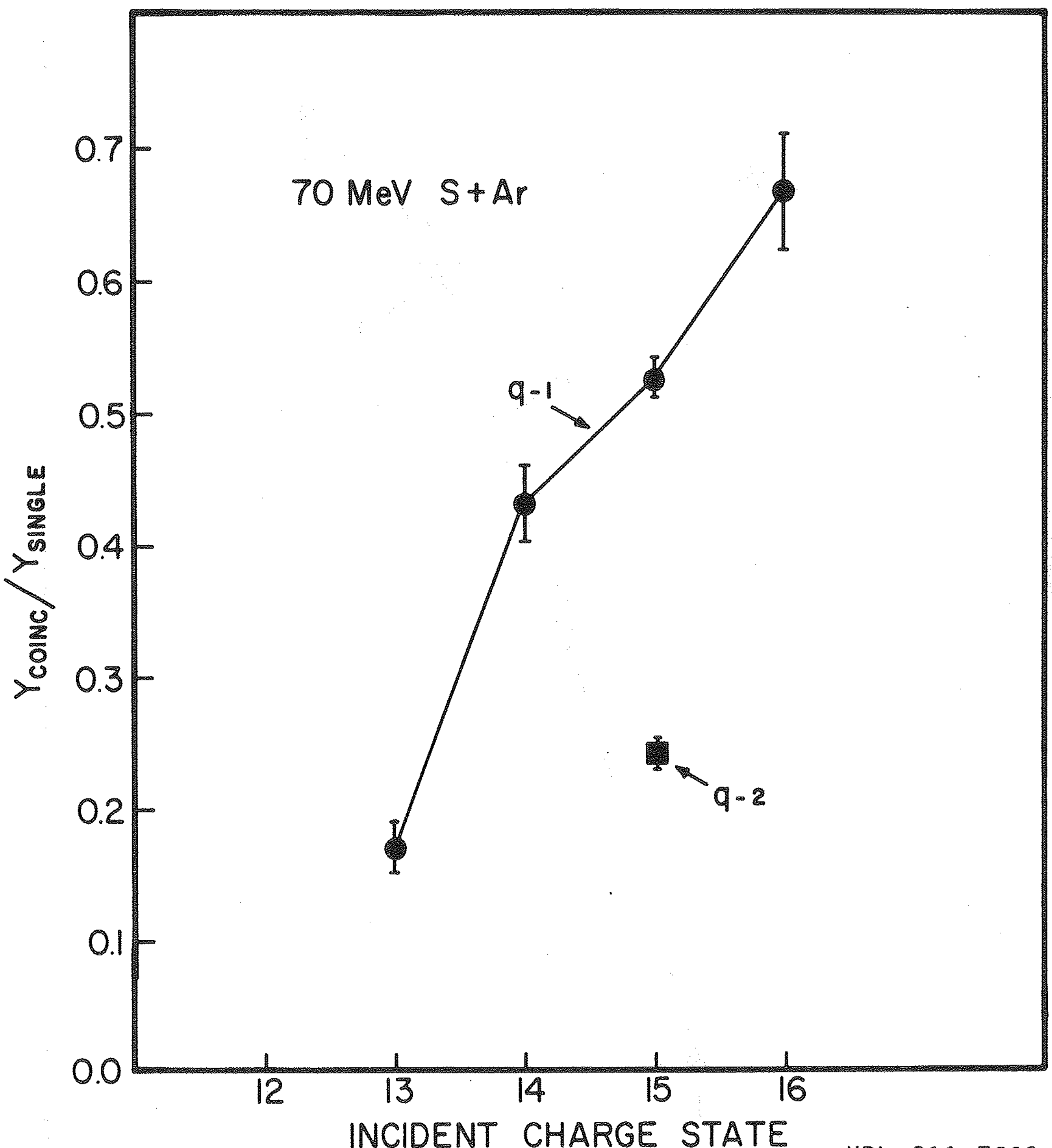

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Fig. 3